

# Entomopathogenic fungi in the biological control of insect pests of soybean crops: progress and prospects in Brazil

Fungos entomopatogênicos no controle biológico de insetos-praga da sojicultura: progresso e perspectivas no Brasil

Hongos entomopatógenos en el control biológico de insectos en cultivos de soja: avances y perspectivas en Brasil

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**RESUMO. Objetivo:** fornecer uma visão integrativa dos estudos relacionados ao desenvolvimento sustentável da sojicultura no Brasil, com ênfase nos principais fungos entomopatogênicos empregados no manejo fitossanitário de insetos-praga. **Métodos:** revisão sistemática da literatura sobre insetos-praga associados à soja e sobre o mercado de bioinseticidas fúngicos, analisando as características biológicas dos microrganismos com base em dados obtidos em múltiplas bases científicas e publicações, compreendendo o período de 2015 a 2025. **Resultados:** as principais pragas da soja pertencem predominantemente às famílias Noctuidae e Pentatomidae. O controle biológico por meio de bioinseticidas fúngicos - principalmente formulações de *Beauveria bassiana*, *Cordyceps fumosorosea* e *Metarhizium anisopliae* - representa aproximadamente 69% do mercado brasileiro de bioinseticidas microbianos. **Conclusão:** o manejo sustentável de pragas da sojicultura no Brasil utilizando formulações fúngicas tem demonstrado alta eficiência.

**Descritores:** Manejo integrado de pragas; Bioinseticidas; Sustentabilidade.

**ABSTRACT. Objectives:** to provide an integrative overview of studies addressing the sustainable development of soybean cultivation in Brazil, with an emphasis on the principal entomopathogenic fungi employed in the phytosanitary management of insect pests. **Methods:** a systematic literature review was conducted on insect pests associated with soybean and the fungal bioinsecticide market, analyzing the biological characteristics of microorganisms based on data retrieved from multiple scientific databases and publications spanning 2015 to 2025. **Results:** the major soybean pests belong predominantly to the families Noctuidae and Pentatomidae. Biological control through fungal bioinsecticides - mainly formulations of *Beauveria bassiana*, *Cordyceps fumosorosea*, and *Metarhizium anisopliae* - represents approximately 69% of the Brazilian microbial bioinsecticide market. **Conclusion:** the sustainable management of soybean pests in Brazil using fungal formulations has demonstrated high efficiency.

**Descriptors:** Integrated Pest Management; Bioinsecticides; Sustainability.

**RESUMEN. Objetivo:** proporcionar una visión integradora de los estudios relacionados con el desarrollo sostenible del cultivo de soja en Brasil, con énfasis en los principales hongos entomopatógenos empleados en el manejo fitosanitario de insectos plaga en los cultivos de soja. **Métodos:** se revisión sistemática de la literatura sobre los insectos plaga asociados a la soja y sobre el mercado de bioinsecticidas fúngicos, analizando las características biológicas de los microorganismos a partir de datos obtenidos en múltiples bases científicas y publicaciones comprendidas entre 2015 y 2025. **Resultados:** las principales plagas de la soja pertenecen predominantemente a las familias Noctuidae y Pentatomidae. El control biológico mediante bioinsecticidas fúngicos —principalmente formulaciones de *Beauveria bassiana*, *Cordyceps fumosorosea* y *Metarhizium anisopliae*— representa aproximadamente el 69% del mercado brasileño de bioinsecticidas microbianos. **Conclusión:** el manejo sostenible de las plagas de la soja en Brasil mediante formulaciones fúngicas ha demostrado una alta eficacia. **Descriptor:** Manejo Integrado de Plagas; Bioinsecticidas; Sostenibilidad.

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**Submissão:** 11 jul 2025

**Aceite:** 10 mar 2026

## INTRODUCTION

*Glycine max* L. (Fabaceae), commonly known as soybean, is an annual herbaceous plant of considerable economic importance worldwide<sup>(1)</sup>. Brazil currently ranks as the leading global producer of soybeans, with grain production estimated at 166.0 million tons for the 2024/25 harvest. This high productivity is largely attributed to the favorable climatic conditions that support soybean cultivation across the country's diverse agricultural regions<sup>(2-3)</sup>. However, despite generally favorable conditions, production is susceptible to fluctuations in abiotic factors, such as temperature variability and water availability, as well as to biotic stresses, including attacks by microorganisms and insect pests<sup>(4)</sup>.

Throughout the soybean growth cycle, various insect species may establish themselves within the crop, feeding on its vegetative and reproductive structures. Defoliating and sucking insects are among the most observed pest groups<sup>(5)</sup>. To mitigate the damage caused by insect pests in soybean cultivation, a range of Integrated Pest Management (IPM) strategies have been implemented, including biological control - a technique that employs living organisms (e.g., arthropods, bacteria, and fungi) as biotic mortality agents to regulate target insect populations<sup>(6)</sup>.

From this perspective, certain entomopathogenic microorganisms can be employed as active ingredients in the formulation of bioinsecticides - inputs considered both sustainable and effective for the biological control of target insect pests<sup>(7-8)</sup>. Among the fungal microorganisms, the species *Beauveria bassiana* (Hypocreales: Cordycipitaceae), *Cordyceps fumosorosea* (Hypocreales: Cordycipitaceae), and *Metarhizium anisopliae* (Hypocreales: Clavicipitaceae) are particularly prominent, collectively representing approximately 69% of the microbial bioinsecticide market in Brazil<sup>(9)</sup>. These entomopathogenic fungi are widely employed in the control of insect pests belonging to the orders Coleoptera, Hemiptera, Lepidoptera, and Hymenoptera<sup>(10)</sup>.

Considering that soybean is one of the most economically significant commodities in Brazil, and that the uncontrolled proliferation of insect pests can lead to substantial losses for producers, this study aims to present a comprehensive literature review addressing the main insect pests affecting soybean crops in the country, as well as the principal entomopathogenic fungi employed in their microbial control. Specifically, this review provides an integrative overview of studies related to the sustainable development of soybean cultivation in Brazil, emphasizing the key entomopathogenic fungi applied in the phytosanitary management of soybean insect pests.

## MATERIAL AND METHODS

This study was conducted as a systematic literature review. Data were collected from the databases of the Ministério da Agricultura, Pecuária e Abastecimento (MAPA) ([www.gov.br/agricultura/pt-br](http://www.gov.br/agricultura/pt-br)), the Agência Nacional de Vigilância Sanitária (Anvisa)

([www.gov.br/anvisa/pt-br](http://www.gov.br/anvisa/pt-br)), and the Companhia Nacional de Abastecimento (CONAB) (<https://antigo.conab.gov.br/info-agro/safras/graos>) to obtain information related to soybean crop production. Additional sources included Google Scholar (<https://scholar.google.com.br/>) and ScienceDirect (<https://www.sciencedirect.com/>).

The review compiled studies reporting the susceptibility of soybean plants to insect pests using the following descriptors: “soybean insect pests” and “occurrence of soybean pest insects in Brazil,” with a focus on publications from the last ten years (2015–2025). Moreover, data on the Brazilian market for microbial bioinsecticides were gathered from the same databases.

The study also examined the representativeness and biological characteristics of the microorganisms employed as biocontrol agents. For this purpose, an additional systematic search was conducted using the descriptors “bioinputs,” “bioinsecticides,” “entomopathogenic fungi,” and “microbial biological control,” focusing on relevant studies published between 2015 and 2025.

## RESULTS

### Soybean cultivation in Brazil

Currently, Brazil is the world’s leading producer of soybeans, with a projected output of 166.0 million tons and an average yield of 3,499 kilograms per hectare for the 2024/25 growing season<sup>(3)</sup>. The United States and Argentina follow, with estimated production volumes of 118.84 million tons and 49.00 million tons, respectively, for the same period<sup>(11)</sup>. Among the Brazilian states, Mato Grosso accounts for the largest share, with an estimated cultivated area of 12,736.1 thousand hectares and a production volume of 47.11 million tons in the 2023/24 harvest<sup>(3)</sup>.

Soybean cultivation represents one of the major agricultural activities in Brazil, providing substantial economic benefits to the population. Its agricultural expansion is closely linked to technological advancements that have facilitated cultivation practices. Soybean accounts for approximately 46% of the use of biological products in the country, highlighting its importance in the expansion of bioinput technologies in Brazil<sup>(12)</sup>. Furthermore, the development of soybean cultivars resistant to glyphosate herbicide has contributed significantly to the crop’s widespread adoption, with glyphosate-resistant varieties currently being the most extensively used by farmers<sup>(13)</sup>.

However, despite its economic importance, soybean production faces significant challenges, particularly due to the emergence of insect pests throughout the crop’s developmental stages. During the vegetative phase, various species of defoliating insects may occur, especially in their larval stages, when soybean leaves are the primary feeding target<sup>(14)</sup>. In the reproductive phase, the pods become attractive to several species of piercing-sucking stink bugs<sup>(15)</sup>. Even with the adoption of transgenic

soybean cultivars, pest infestations continue to be reported, causing considerable damage to the crop<sup>(16)</sup>.

Since its introduction to the market, Bt soybean - a variety expressing insecticidal proteins - has exhibited susceptibility to insect pest attacks, with increasing vulnerability recently observed, as in the case of the whitefly *Bemisia tabaci* (Gennadius, 1889) (Hemiptera: Aleyrodidae)<sup>(16)</sup>, as well as other defoliating insects. Continuous exposure of pest populations to Bt residues may promote the predominance of resistant individuals and contribute to the resurgence of secondary pests, as has been documented for stink bugs<sup>(17)</sup>. Moreover, climate change and global warming represent additional challenges, as rising temperatures can adversely affect soybean yield by directly influencing insect pest populations - expanding their geographic distribution, increasing oviposition rates and the number of generations per season, and accelerating developmental cycles<sup>(18)</sup>.

Due to the high susceptibility of soybean cultivars, farmers are required to conduct regular monitoring of their cultivated areas. In Brazil, when infestations reach or exceed 30% by defoliating insects during the vegetative stage, or 15% by piercing-sucking insects during the reproductive stage, the implementation of Integrated Pest Management (IPM) is recommended<sup>(19)</sup>. Defoliation exceeding 66% is considered to place the crop at high risk<sup>(20)</sup>. For stink bugs, the presence of two individuals per linear meter in areas with pods  $\geq 0.5$  cm indicates the need for IPM interventions<sup>(19)</sup>.

### **Insect pests in soybean crops**

Soybean crops can host numerous arthropods, particularly insect pests, that feed on various plant structures throughout different stages of the crop development cycle, from germination to grain formation, resulting in significant economic losses for producers in this sector (Tab. 1)<sup>(4)</sup>. These insects can be classified as primary, secondary, or occasional pests, depending on their period of occurrence, population density, and the extent of damage inflicted on the host plant<sup>(21)</sup>.

Following germination, soybean plant roots can be attacked by certain species of mining insects<sup>(22)</sup>. During the vegetative growth stages, defoliating caterpillars may emerge, causing leaf damage that compromises photosynthetic capacity and potentially leads to yield losses<sup>(21)</sup>. In the later developmental stages, piercing-sucking stink bugs interfere with soybean grain development, reducing grain size and altering coloration; moreover, these insects can facilitate contamination by transmitting phytopathogenic fungi during feeding<sup>(15)</sup>.

The spatial distribution of insects varies across different soybean-growing areas. Juvenile and adult insects may exhibit differing population densities due to their behavior, feeding habits, genetic traits, and environmental factors<sup>(23-24)</sup>. Specific distribution patterns of different developmental stages of beetles in soybean fields can be influenced by factors such as plant health, adult sex, and the

presence of other organisms, as observed in *Sternechus subsignatus* Boheman, 1836 (Coleoptera: Curculionidae)<sup>(25)</sup>.

**Table 1.** Economically important insect pests of soybean (*Glycine max L.*) reported in the literature over the last decade (2015–2025). Vegetative stage: germination, emergence, and development. Reproductive stage: flowering, seed development, and maturity.

Species	Family	Phenological stage of the plant	Reference
<i>Anticarsia gemmatalis</i>	Noctuidae	Vegetative	CONTE <i>et al.</i> , 2017
<i>Agrotis ipsilon</i>	Noctuidae	Vegetative and Reproductive	HEINZELMANN <i>et al.</i> , 2024
<i>Helicoverpa armigera</i>	Noctuidae	Vegetative and Reproductive	PINTO <i>et al.</i> , 2017
<i>Chrysodeixis includens</i>	Noctuidae	Vegetative and Reproductive	CARNEVALI <i>et al.</i> , 2024
<i>Spodoptera frugiperda</i>	Noctuidae	Vegetative and Reproductive	CARNEVALI <i>et al.</i> , 2024
<i>Spodoptera eridania</i>	Noctuidae	Vegetative and Reproductive	CARNEVALI <i>et al.</i> , 2024
<i>Spodoptera cosmioides</i>	Noctuidae	Vegetative and Reproductive	CARNEVALI <i>et al.</i> , 2024
<i>Spodoptera albula</i>	Noctuidae	Vegetative and Reproductive	CARNEVALI <i>et al.</i> , 2024
<i>Rachiplusia nu</i>	Noctuidae	Vegetative and Reproductive	GODÓI <i>et al.</i> , 2025
<i>Trichoplusia ni</i>	Noctuide	Vegetative	SPECHT <i>et al.</i> , 2019
<i>Bemisia tabaci</i>	Aleyrodidae	Vegetative and Reproductive	ARNEMANN <i>et al.</i> , 2019
<i>Euchistus heros</i>	Pentatomidae	Reproductive	CARNEVALI <i>et al.</i> , 2024
<i>Scaptocoris castânea</i>	Pentatomidae	Reproductive	HEINZELMANN <i>et al.</i> , 2024
<i>Nezara viridula</i>	Pentatomidae	Reproductive	SALDANHA <i>et al.</i> , 2024
<i>Edessa meditabunda</i>	Pentatomidae	Reproductive	SALDANHA <i>et al.</i> , 2024
<i>Dichelops furcatus</i>	Pentatomidae	Reproductive	SALDANHA <i>et al.</i> , 2024
<i>Diceraeus melacanthus</i>	Pentatomidae	Reproductive	SALDANHA <i>et al.</i> , 2024
<i>Piezodorus guildinii</i>	Pentatomidae	Reproductive	SALDANHA <i>et al.</i> , 2024
<i>Sternechus subsignatus</i>	Curculionidae	Reproductive	SOCIÁS <i>et al.</i> , 2016
<i>Myochorus armatus</i>	Chrysomelidae	Vegetative	PERINI <i>et al.</i> , 2024
<i>Diabrotica speciosa</i>	Chrysomelidae	Vegetative and Reproductive	CAMPOS <i>et al.</i> , 2018

<i>Lagria villosa</i>	Tenebrionidae	Vegetative and Reproductive	CAMPOS <i>et al.</i> , 2018
<i>Cerotoma sp.</i>	Chrysomelidae	Vegetative and Reproductive	HEINZELMANN <i>et al.</i> , 2024

In recent growing seasons, the composition of major soybean pests in Brazil has varied according to region and crop development stage. In the southern region, *Anticarsia gemmatalis* Hübner, 1818 (Lepidoptera: Erebididae) and *Chrysodeixis includens* Walker, 1858 (Lepidoptera: Noctuidae) have been the most common defoliators, while the stink bugs *Euschistus heros* Fabricius, 1798 (Hemiptera: Pentatomidae), *Nezara viridula* Linnaeus, 1758 (Hemiptera: Pentatomidae), and *Dichelops furcatus* Fabricius, 1775 (Hemiptera: Pentatomidae) have predominated among the piercing-sucking insects. In states such as Paraná, *C. includens* and *Rachiplusia nu* Guenée, 1852 (Lepidoptera: Noctuidae) have shown high population densities up to the end of the soybean cycle, with *E. heros* remaining the most prevalent stink bug species<sup>(14, 26)</sup>. In the Southeast, particularly in Minas Gerais, *Helicoverpa armigera* Hübner, 1805 (Lepidoptera: Noctuidade) has been reported in areas where its presence was previously limited, along with frequent occurrences of *C. includens*, *E. heros*, and *Diabrotica speciosa* Germar, 1824 (Coleoptera: Chrysomelidae)<sup>(27–28)</sup>. In the Central-West region, the *Spodoptera* complex and *E. heros* have stood out, with *Spodoptera eridania* Stoll, 1781 (Lepidoptera: Noctuidae) and *A. gemmatalis* predominant in certain states such as Mato Grosso<sup>(27)</sup>.

Recent studies indicate that *R. nu* has surpassed *C. includens* in frequency in both Bt and conventional cultivars across major soybean-producing states<sup>(29)</sup>. Stink bug populations reach their peak during the final stages of grain filling, and approximately 60% of the insecticides applied in soybean fields target this pest group<sup>(30)</sup>. Although *A. gemmatalis* was historically the main lepidopteran pest of soybean, this position has increasingly been occupied by species from the *Spodoptera* complex, *H. armigera*, *R. nu*, and *Trichoplusia ni*, which together are responsible for up to 80% of crop losses<sup>(28, 31–32)</sup>.

Emerging pests, such as *Myochorus armatus* Baly, 1865 (Coleoptera: Chrysomelidae) and *B. tabaci*, have recently expanded their distribution into southern regions<sup>(33–34)</sup>. The establishment of new species can shift agroecosystem dynamics and promote the emergence of novel pest threats<sup>(35)</sup>. Even in no-till systems with crop rotation, pest populations may persist due to year-round favorable climatic conditions<sup>(36)</sup>. Another relevant factor is that species within the *Spodoptera* genus have shown increased resistance to transgenic crops and temperature variations, making soybean crops more susceptible to their infestations<sup>(37)</sup>. This spatiotemporal behavior, combined with constant

exposure to management practices such as intensive insecticide use and Bt cultivation, imposes strong selective pressure on populations, favoring individuals with resistance traits<sup>(38)</sup>.

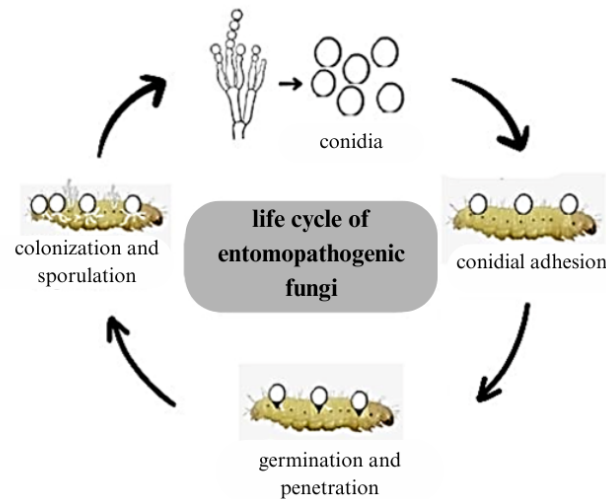
## DISCUSSION

### Entomopathogenic fungi and their use as bioinsecticides

Entomopathogenic fungi are insect parasites widely distributed across the globe and can be isolated from air, soil, plants, live insects, or their cadavers<sup>(39)</sup>. These organisms play a significant role in the natural regulation of insect populations and perform important ecosystem functions. In biological control, they are employed as biotic mortality agents within Integrated Pest Management (IPM) programs<sup>(7)</sup>.

Infection by filamentous fungi from the families Clavicipitaceae and Cordycipitaceae follows a similar sequential process. Initially, conidia come into contact with the host cuticle and adhere to its surface. Following adhesion, germination occurs along with the formation of an appressorium. This process is assisted by hydrolytic enzymes such as chitinases, lipases, and proteases, which facilitate penetration by degrading the cuticular layers and generating the germ tube that invades epithelial cells. Insect colonization proceeds through invasion of the cuticle and epithelium, followed by hyphal growth reaching the hemolymph. At this stage, the fungus intensifies its proliferation, exploits available nutrients, colonizes internal tissues, and modulates the host's immune system by inhibiting its defense mechanisms (Fig. 1)<sup>(40)</sup>.

The interspecific relationship between fungi and insects occurs naturally and has been described for centuries, attributed to the coevolution of both groups. Today, this interaction is reflected in Integrated Pest Management (IPM) strategies and the Brazilian bioinsecticide market, where commercial products are widely used based on active ingredients such as conidia and spores from fungal genera including *Metarhizium*, *Beauveria*, *Cordyceps*, and *Trichoderma*<sup>(9, 40)</sup>.

**Figure 1.** Schematic representation of the life cycle of entomopathogenic fungi.

Source: Produced by the authors (2025).

### ***Metarhizium anisopliae* (Hypocreales: Clavicipitaceae)**

*Metarhizium anisopliae* (Fig. 2) is an entomopathogenic fungus belonging to the genus *Metarhizium*, family Clavicipitaceae, and order Hypocreales<sup>(41)</sup>. This genus is considered either saprophytic or endophytic, occurring in soils, particularly in the rhizosphere of plants, and parasitizing arthropods, especially insects and ticks<sup>(42)</sup>. In Brazilian soils, *M. anisopliae* can be isolated from crop fields and agricultural soils and differs from fungi of the genera *Beauveria* and *Cordyceps* due to its greater resistance to environmental stressors and other microorganisms<sup>(43)</sup>.

The filamentous anamorphic fungus *M. anisopliae* reproduces asexually, producing spores with a characteristic gray-green coloration. Within the Clavicipitaceae family, this species is considered a model organism due to its potential to promote more sustainable pest management compared to chemical insecticides. Its conidia are widely utilized by bioproduction companies as active ingredients in the formulation of commercial fungal pesticides (Table 2). Studies evaluating the virulence of different *M. anisopliae* isolates have demonstrated promising results against key insect pests, particularly stink bugs, including eggs and nymphs of *E. heros*. Moreover, *M. anisopliae* has shown potential for controlling defoliating caterpillars such as *A. gemmatalis*, *C. includens*, *H. armigera*, and *Spodoptera frugiperda* Smith, 1797 (Lepidoptera: Noctuidae), highlighting its broad-spectrum applicability in integrated pest management programs<sup>(42–47)</sup>.

Studies evaluating the virulence of different *M. anisopliae* isolates have shown promising results against insect pests, particularly in the control of stink bugs, including eggs<sup>(44)</sup> and nymphs<sup>(45)</sup> of *E. heros*. Phytosanitary management of other pest species has also yielded encouraging outcomes,

with potential for controlling defoliating caterpillars such as *A. gemmatalis*, *C. includens*, *H. armigera*, and *S. frugiperda*<sup>(46-47)</sup>.

### ***Beauveria bassiana* (Hypocreales: Cordycipitaceae)**

*Beauveria bassiana* (Fig. 2) is another fungus with entomopathogenic properties. This species belongs to the phylum Ascomycota, class Sordariomycetes, order Hypocreales, and family Cordycipitaceae. It was first isolated in 1835 in Italy, infecting *Bombyx mori* Linnaeus, 1758 (Lepidoptera: Bombycidae)<sup>(48)</sup>. Currently, it is known that *B. bassiana* can infect a wide range of insect pests across more than six orders<sup>(49)</sup>, making it one of the most widely utilized entomopathogenic fungi in the production of biological inputs<sup>(9)</sup> (Table 2).

**Table 2.** Some commercial products formulated with entomopathogenic fungi and registered with Ministério da Agricultura, Pecuária e Abastecimento (MAPA) in the last ten years (2015-2025).

Commercial product	Manufacturer	Active ingredient
BassiControl®	Innova Ltda	<i>Beauveria bassiana</i>
HizoBio® WP	HizoBio Controle Biológico Ltda	<i>Beauveria bassiana</i>
Biobassi®	Biomip Agentes biológicos Ltda	<i>Beauveria bassiana</i>
Botanigard® WP	Mitsui & Co (Brasil) S.A	<i>Beauveria bassiana</i>
Bove K®	Koppert do Brasil Holding S.A	<i>Beauveria bassiana</i>
Bovenat®	Bionat Soluções Biológicas Ltda	<i>Beauveria bassiana</i>
BeauveControl®	Simbiose Ltda	<i>Beauveria bassiana</i>
Boveril Evo®	Koppert do Brasil Holding S.A	<i>Beauveria bassiana</i>
Bio Phygga®	Bionat Soluções Biológicas Ltda	<i>Metarhizium anisopliae</i>
EcoMeta®	Toyobo do Brasil Produtos Biológicos Ltda	<i>Metarhizium anisopliae</i>
Metabio®	Coopavel Cooperativa Agroindustrial	<i>Metarhizium anisopliae</i>
Metacombat Pro®	Viva Soluções Biológicas Ltda	<i>Metarhizium anisopliae</i>
Metamip®	Promip Manejo Integrado de Pragas Ltda	<i>Metarhizium anisopliae</i>
Octane®	Koppert do Brasil Holding S.A	<i>Cordyceps fumosorosea</i>
Isa 3®	Vital Brasil Chemical Ltda	<i>Cordyceps fumosorosea</i>
IsaControl®	Simbiose Indústria e Comércio de Fertilizantes e Insumos Microbiológicos Ltda	<i>Cordyceps fumosorosea</i>
Izaturbo®	Vittia S.A	<i>Cordyceps fumosorosea</i>

Source: MAPA (2025).

Upon reaching the hemolymph, the hyphae of *B. bassiana* can synthesize and release toxins or secondary metabolites, including beauvericin, bassianin, bassianolide, beauverolides, tenelin,

oosporein, oxalic acid, and calcium oxalate crystals. These compounds may exert insecticidal, cytotoxic, and fungicidal activities, among other effects yet to be fully elucidated<sup>(50)</sup>. The observed impacts on target pests result from the cumulative action of these molecules within the host and are influenced by factors such as the physiological state and life cycle of *B. bassiana*<sup>(50)</sup>.

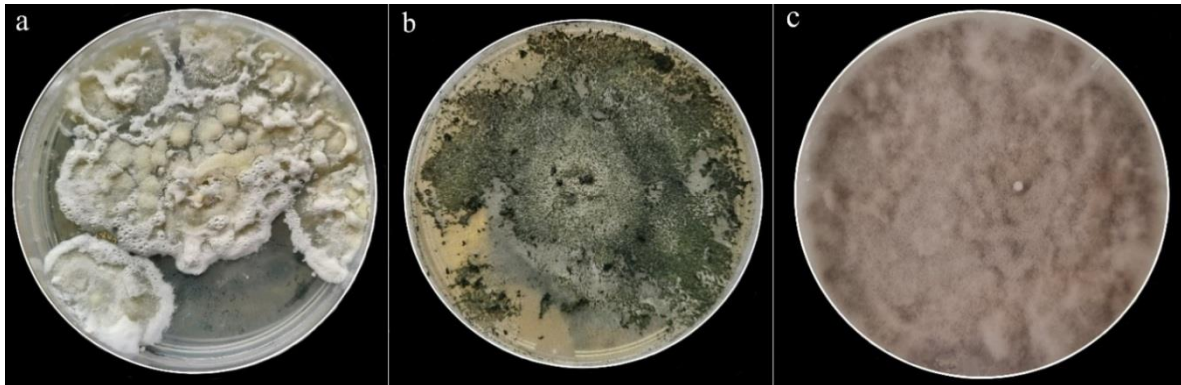
In soybean cultivation, for example, the application of *B. bassiana* contributes to the population regulation of *B. tabaci*<sup>(51)</sup>, *S. frugiperda*, and *C. includens*<sup>(52)</sup>. However, even in the absence of deliberate application, *B. bassiana* can be naturally found across all Brazilian biomes<sup>(53)</sup> and in regions with severe cold climates, such as Russia<sup>(54)</sup>. Additionally, it has been reported to cause epizootics in other parts of the world, including *B. mori* in China<sup>(55)</sup>.

### ***Cordyceps fumosorosea* (Hypocreales: Cordycipitaceae)**

*Cordyceps fumosorosea* (Fig. 2) has a broad distribution across various geographical regions, ranging from tropical to Arctic climates<sup>(56)</sup>. This microorganism is capable of infecting diverse insect species but predominantly affects Lepidoptera and Hemiptera<sup>(10)</sup>. For a long time, it was described as *Isaria fumosorosea*, but in the last decade, based on recent phylogenetic analyses of nuclear genes from different fungal species, it has been reclassified within the genus *Cordyceps*<sup>(57)</sup>.

In Brazil, *C. fumosorosea* can be isolated from various habitats and is commonly found in natural environments and insect cadavers, unlike strains of *M. anisopliae*, which are more prevalent in cultivated fields<sup>(43)</sup>. The complex of different *C. fumosorosea* strains has been the focus of research in recent years due to their success in pest control and their high germination speed on the cuticle of host insects<sup>(56)</sup>, characteristics that have enabled their use as active ingredients in bioinsecticides. Within the host, the fungus releases enzymes that dissolve tissues and organs, obtaining the necessary nutrients for its growth and development<sup>(57)</sup>. Among the synthesized toxins, the depsipeptide known as beauvericin, also produced by *B. bassiana*, stands out<sup>(39, 57)</sup>.

**Figure 2.** Entomopathogenic fungi of the three most registered species in Brazil, cultured on potato dextrose agar (PDA) medium and maintained in an incubator at 27 °C. a) *Beauveria bassiana*; b) *Metarhizium anisopliae*; c) *Cordyceps fumosorosea*.



Source: Produced by the authors.

### **Bioinsecticide market in Brazil**

Bioinsecticides can be classified as microbiological, macrobiological, biochemical, and semiochemical<sup>(58)</sup>. Microbiological bioinsecticides are formulated with entomopathogenic agents such as bacteria, fungi, nematodes, protozoa, and viruses (with some exceptions)<sup>(7)</sup>. In Brazil, Anvisa classifies biological products according to toxicological risks, categorizing them as low risk or as having potential toxicological harm, based on Collegiate Board Resolution (RDC) No. 294 of 2019<sup>(59)</sup>. The commercialization and production of these products are authorized by Ibama under Decree 4074/2002<sup>(60)</sup>.

The world's first commercial bioinsecticide, Sporeine, was produced in 1950 in France, based on spores of *Bacillus thuringiensis* (Bacillales: Bacillaceae)<sup>(8)</sup>. Over time, products derived from this microorganism have spread globally, forming the foundation for the population control of lepidopteran pests due to their action on the digestive system of these insects<sup>(8, 61)</sup>. Currently, the bio-inputs market is experiencing growing demand, supported by public policies that promote the development of sustainable agriculture<sup>(7, 62)</sup> and the establishment of national programs, such as the National Bio-inputs Program, which supports the development of innovative sustainable technologies<sup>(63)</sup>.

The rise in the adoption of bioinsecticides is driven by several factors, including enhanced efficacy and quality within integrated pest management programs, higher performance compared to chemical insecticides, reduced selection pressure on resistant pest populations, simplified residual management, lower carbon and other greenhouse gas emissions, and labor flexibility<sup>(64)</sup>. In Brazil,

this growth is largely attributed to regulatory exemptions, which simplify and accelerate the registration process for bioinsecticides, thereby attracting investment and companies to the sector<sup>(65)</sup>.

Among microbiological bioinsecticides, entomopathogenic fungi play a prominent role. These microorganisms, naturally found in soil, air, plants, and in both living and dead insects, are fundamental agents in the natural regulation of insect populations<sup>(39-40)</sup>. In the context of biological control, they are widely used due to their ability to act as mortality agents within integrated pest management programs<sup>(6, 9, 41)</sup>.

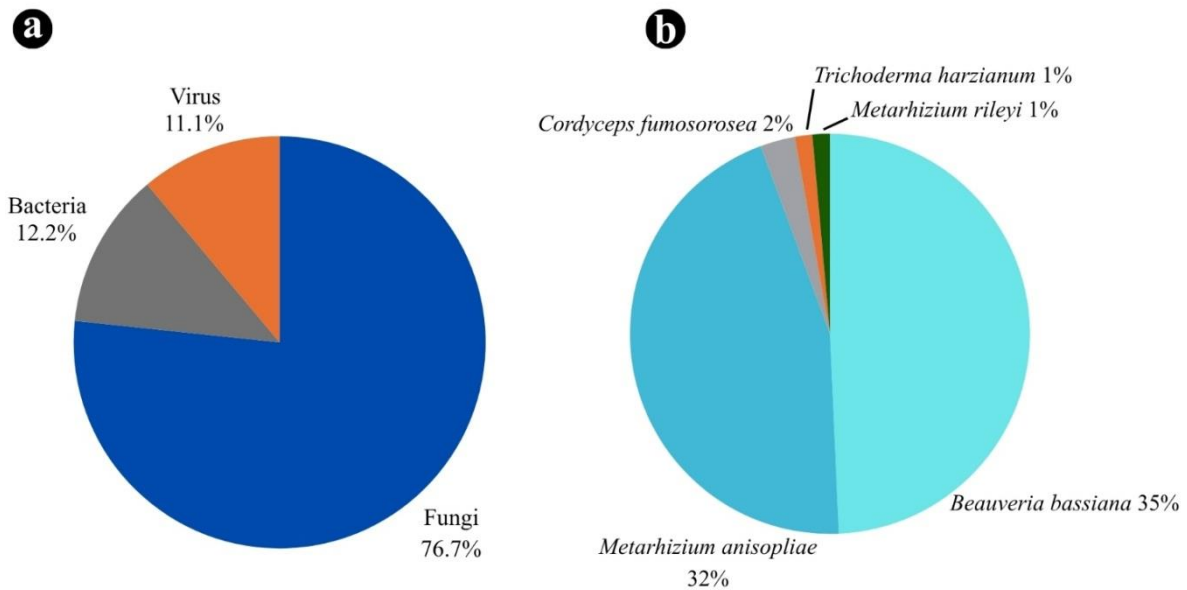
Currently, there are records of 352 products formulated with entomopathogenic microorganisms in Brazil<sup>(9)</sup>. Biological products belong to three main groups: bacteria (19.4%), fungi (69.7%), and viruses (10.9%) (Fig. 3). Most fungal bioinsecticides contain *B. bassiana* and *M. anisopliae* as active ingredients, representing 35.6% and 32%, respectively, followed by *C. fumosorosea* (formerly *Isaria*), *M. rileyi* (Hypocreales: Clavicipitaceae), and *Trichoderma harzianum* (Hypocreales: Hypocreaceae), with 2.2%, 1.10%, and 0.8%, respectively<sup>(9)</sup>. Microbial bioinsecticides can be formulated as wettable powders, oil suspensions, liquid solutions, or concentrated suspensions and are marketed under various trade names in Brazil.

### Strategies for mitigation and management of resistance

To prevent the selection of soybean pest insect populations resistant to entomopathogenic fungi, a range of integrated measures must be considered. The application of commercial products formulated with fungi should be combined with other management strategies, including the joint use of additional biological agents, such as different microbial strains, and the implementation of refuge areas. Adoption of these practices reduces the risk factors associated with the development of resistance in insect populations<sup>(66)</sup>.

The synergistic interaction between entomopathogenic fungi, bioinsecticides, and microorganisms in the soil microbiota of agricultural areas, along with compatible chemical molecules, can significantly contribute to resistance mitigation by enhancing mortality rates, as reported for *R. nu*, a caterpillar feeding on soybean plants<sup>(67)</sup>. In this context, rotating fungal bioinsecticides with other biological control agents, combined with diversified integrated pest management (IPM) practices such as cultural and genetic control, becomes essential<sup>(68)</sup>.

**Figure 3.** a) Percentages of the three main groups (bacteria, fungi, and viruses). B) Percentage distribution of entomopathogenic fungi used in the formulation of microbial bioinsecticides registered with the Ministério da Agricultura, Pecuária e Abastecimento (MAPA).



Source: Produced by the authors based on the MAPA database (2025).

Biotechnology plays a key role in this scenario, offering significant advances in bioprospecting and the genetic improvement of fungal isolates<sup>(69)</sup>. The selection of strains with high pathogenicity and the prospecting of genetically diverse isolates not yet available in the Brazilian market represent a strategy to increase the genetic variability of entomopathogenic fungi and, consequently, reduce the risk of resistance development in pest populations<sup>(69)</sup>. However, such selection must be carried out cautiously, since isolates with high environmental persistence may promote continuous exposure of insects to control agents, thereby favoring the selection of individuals less susceptible to the pathogen<sup>(70)</sup>.

## CONCLUSION

Soybean cultivation in Brazil remains highly susceptible to a diverse range of insect pests, predominantly from the Noctuidae and Pentatomidae families, which continue to challenge sustainable production. Entomopathogenic fungi have demonstrated significant potential as biological control agents within integrated pest management (IPM) programs, providing environmentally friendly alternatives to chemical insecticides. The species *B. bassiana*, *M. anisopliae*, and *C. fumosorosea* are the primary microbial agents actively used in bioinsecticide

formulations. However, the persistent exposure of pest populations to these biological agents, combined with climate change and evolving pest dynamics, underscores the critical need for diversified management strategies.

The integration of biotechnology, including the genetic improvement of entomopathogenic fungal isolates, the development of novel soybean cultivars, and the implementation of innovative agronomic practices, provides promising strategies to enhance pest control efficacy and delay the development of resistance. Maintaining continuous monitoring and early detection of resistance is essential to preserve the effectiveness of fungal bioinsecticides and other biological control tools. Advances in molecular technologies, such as RNA interference (RNAi), combined with the design of synergistic bioinsecticide formulations that pair entomopathogenic fungi with compatible chemical or biological agents, represent a proactive approach to mitigating resistance while optimizing pest management. Ultimately, the adoption of a holistic and adaptive Integrated Pest Management (IPM) framework - integrating biological, chemical, genetic, and cultural control strategies - will be critical for achieving sustainable soybean production in Brazil and globally.

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